

A Hybrid-Magnet Rotor Topology for Demagnetization-Resistant PMaSynRMs Using Kriging-NSGA-III Optimization

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ABSTRACT: Conventional ferrite-based, permanent magnet-assisted, synchronous reluctance motors (PMaSynRMs) suffer from low torque density and are vulnerable to irreversible demagnetization under heavy-load conditions due to reverse armature field. To address this, this paper proposes a hybrid-magnet rotor topology in which ferrite and NdFeB magnets are arranged in series along the flux path within each U-type flux barrier (NdFeB on the air-gap side, ferrite on the inner side), while the three radially layered U-type branches are connected magnetically in parallel. Within each barrier, the magnetomotive forces of the two magnet types superpose to enhance the excitation flux; meanwhile, a dual synergistic mechanism — outer NdFeB shielding and flux shunting via parallel rotor bridges — suppresses the demagnetizing field. To tackle the 15-dimensional optimization problem, a Kriging-NSGA-III framework incorporating Pearson sensitivity screening is established. Finite-element results show that, compared to the benchmark all-ferrite machine, the optimized motor achieves a 20.78% increase in average torque, torque ripple reduction from 18.80% to 8.07%, and 89.49% efficiency. The benchmark exhibits local irreversible demagnetization at 3 times rated d -axis current, whereas the proposed topology shows no observable demagnetization even at 6 times rated current, validating the effectiveness of the proposed hybrid topology and optimization strategy.

1. INTRODUCTION

The inherent vulnerability of ferrite magnets to irreversible demagnetization under heavy-load d -axis armature reaction remains a primary bottleneck limiting the widespread adoption of low-cost PMaSynRMs in industrial drive applications [1–3]. While the strategic reduction of rare-earth content addresses material cost and supply chain risks, it often compromises the rotor's magnetic robustness under extreme overload conditions. Consequently, designing a hybrid-magnet topology that not only retains the torque density advantages of PMaSynRMs but also provides a substantial safety margin against extreme demagnetizing fields is critically important for fan, pump, and compressor systems requiring high reliability.

Existing hybrid-magnet PMaSynRMs can be classified into parallel, series, and series-parallel hybrid configurations according to magnet arrangement. Parallel configurations enhance air-gap fundamental flux density through flux concentration but struggle to suppress torque harmonics effectively [4–7]; series configurations can adjust the equivalent magnetomotive force, but most designs do not incorporate demagnetization resistance as a design consideration [8]; series-parallel hybrid topologies achieve balanced overall performance but suffer from complex rotor manufacturing and high cost [9]. For ferrite demagnetization, existing mitigation measures mostly adopt single approaches such as auxiliary magnetic holes or localized rare-earth cladding, which only marginally improve the operating points of permanent magnets and cannot with-

stand extreme overload conditions of several times the rated current [10–12]. In contrast, the series hybrid configuration has been consistently demonstrated to feature a higher demagnetization withstand capability compared to its parallel counterpart, as the high-coercivity rare-earth magnet in a series connection can support the low-coercivity ferrite magnet against irreversible demagnetization [13]. However, most existing optimization studies treat demagnetization resistance only as a post-verification check rather than an explicit magnetic-circuit design criterion, leaving ferrite segments in most hybrid machines vulnerable to localized flux concentration and insufficient operating point margin under extreme overload d -axis currents [11].

Geometric optimization of electric machines is a typical high-dimensional nonlinear problem, where the ever-increasing number of design variables poses a significant challenge to conventional population-based search algorithms. The exponential expansion of the search space, commonly referred to as the curse of dimensionality, severely degrades both the convergence speed and solution quality of many metaheuristics [14, 15]. To mitigate this issue, various dimensionality-reduction strategies have been proposed to compress the original high-dimensional design space into a lower-dimensional latent or representative subspace, thereby improving the efficiency and numerical stability of the subsequent optimization process [16, 17]. Even with such reductions, however, the search efficiency of algorithms, such as particle swarm optimization and differential evolution, remains limited, as they are inherently prone to stagnation at local optima in multi-objective scenarios. Furthermore, the crowding-distance-based

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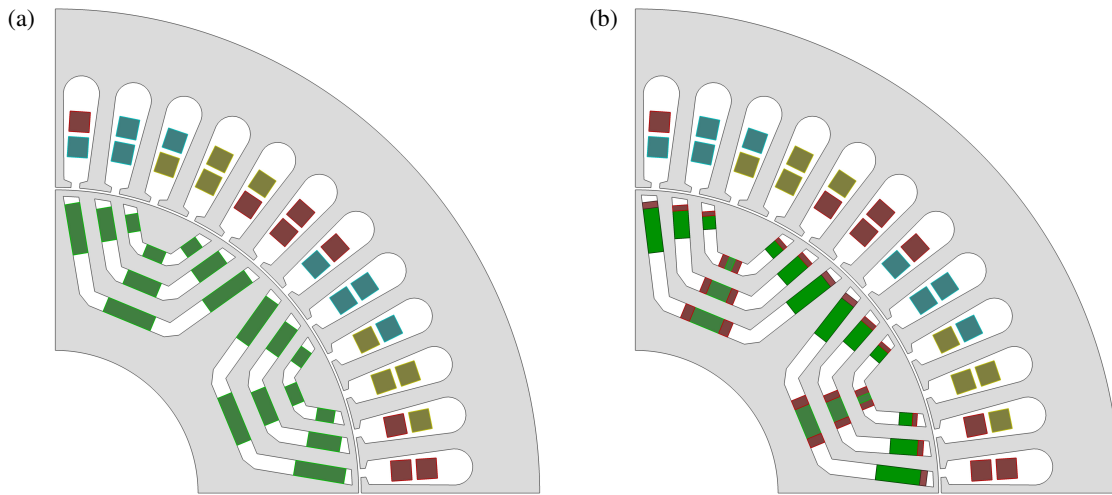


FIGURE 1. Schematic diagram of motor topologies. (a) Conventional U-type rotor and (b) the proposed hybrid-magnet rotor.

selection mechanism of NSGA-II struggles to maintain a well-distributed Pareto front when handling three or more conflicting objectives [18]. In contrast, NSGA-III, with its uniformly distributed reference-point mechanism, exhibits superior convergence and diversity performance in multi-objective optimization [18]. Meanwhile, finite-element simulations remain computationally prohibitive for iterative evaluation, while the Kriging surrogate model can significantly reduce computational cost while maintaining high prediction accuracy and has been widely adopted in multi-objective optimization of various electric machines [19–23]. By integrating dimensionality-reduction techniques with surrogate-assisted multi-objective optimization, the overall design efficiency can be substantially enhanced, enabling a more effective exploration-exploitation trade-off within a limited evaluation budget.

In previous work, we have investigated PMaSynRMs from several perspectives. One work adopted a segmented non-uniform air gap combined with hybrid magnets to reduce torque ripple and NdFeB consumption [24]; another designed an asymmetric flux-barrier structure to align the peak current angles of permanent-magnet and reluctance torques [25]. Both studies focused primarily on steady-state torque performance and did not address magnetic-circuit flux-shunting design against heavy-load demagnetizing fields, leaving ferrite demagnetization risk unresolved.

To fill this gap, this paper proposes a layered hybrid-magnet rotor topology. Within each U-shaped flux barrier, NdFeB magnets are placed on the air-gap side and ferrite magnets on the inner rotor side, for both d -axis radial segments and circumferential end segments. Under radial magnetization, the two magnet materials are sequentially arranged along the flux path within each branch, and the d -axis and end-side branches within each layer form parallel magnetic paths, and the three layers also operate magnetically in parallel, with rotor iron bridges forming multiple low-reluctance bypass loops. A sensitivity-driven dimension-reduction Kriging-NSGA-III optimization framework is built to verify its superiority in torque improvement, torque ripple suppression, and overload anti-

demagnetization capability, and further elaborates the dual synergistic demagnetization suppression mechanism to achieve a substantial safety margin against extreme multiple-time rated overload.

2. MOTOR STRUCTURE AND WORKING PRINCIPLE

2.1. Motor Topology

The benchmark machine adopts a three-layer U-type flux-barrier rotor fully filled with Y30 ferrite. In the proposed topology, each flux barrier adopts a layered PM arrangement: N35 NdFeB is placed on the air-gap side and Y30 ferrite on the rotor-yoke side for both d -axis straight segments and circumferential end segments. The two machines share identical stator geometry and overall dimensions and differ only in rotor permanent magnet configuration. Key parameters are listed in Table 1, and rotor cross-sections are shown in Figs. 1(a) and 1(b).

TABLE 1. Comparison of key parameters between the initial motor and the optimized motor.

Parameter	Optimized motor	Initial motor
Rated output power (kW)	2.2	2.2
Rated speed (rpm)	1000	1000
Rated phase current (A)	5	5
Air-gap length (mm)	0.5	0.5
Permanent magnet material	Y30/N35	Y30
Stator outer diameter (mm)	95	95
Number of poles/slots	8/48	8/48

2.2. Torque Enhancement Mechanism

PMaSynRMs generate torque mainly from reluctance torque produced by d - q axis inductance difference, plus permanent magnet torque from the interaction between the PM field and stator field. The electromagnetic torque of the PMaSynRM can

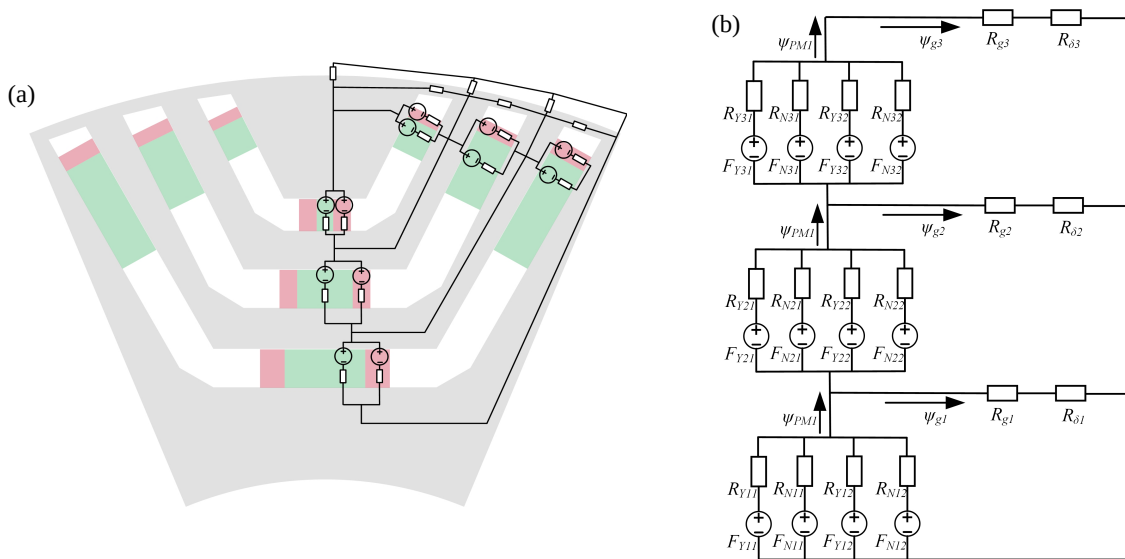


FIGURE 2. No-load equivalent magnetic circuit. (a) No-load magnetic circuit model and (b) Simplified no-load equivalent circuit.

be expressed as [26]:

$$T_e = T_{pm} + T_{re} = \frac{3}{2}p[\psi_{PM}i_q + (L_d - L_q)i_d i_q] \quad (1)$$

where p is the number of pole pairs; i_s is the stator current; and β is the angle between i_s and the d -axis.

Different from the parallel hybrid-magnet rotor in our previous work [24], where ferrite and NdFeB magnets were arranged in separate radial flux branches, this paper constructs a three-layer cascaded hybrid magnet structure. Within each flux-barrier layer, two groups of ferrite and NdFeB magnets are placed in parallel magnetic branches. A lumped parameter magnetic circuit model with double subscripts is established to analyze the magnetomotive force (MMF) superposition effect. The physical no-load magnetic circuit model is shown in Fig. 2(a), and its simplified equivalent circuit is illustrated in Fig. 2(b).

Symbol definitions are listed as follows:

$k = 1, 2, 3$ denotes three radial flux-barrier layers;

$i = 1, 2$ represents two parallel magnet groups within each layer;

F_{Yki} and R_{Yki} are the magnetomotive force and reluctance of ferrite magnets (subscript Y) on the i -th group of the k -th layer;

F_{Nki} and R_{Nki} correspond to the MMF and reluctance of NdFeB magnets (subscript N);

R_{gk} and $R_{\delta k}$ are air-gap reluctance and rotor iron-bridge reluctance of the k -th layer.

Based on Thevenin's theorem, the equivalent flux linkage and equivalent reluctance of each flux-barrier layer in the sim-

plified circuit are expressed as Eq. (2):

$$\begin{cases} \Psi_{eqk} = N \sum_{i=1}^2 \left(\frac{F_{Yki}}{R_{Yki}} + \frac{F_{Nki}}{R_{Nki}} \right) \\ \frac{1}{R_{eqk}} = \sum_{i=1}^2 \left(\frac{1}{R_{Yki}} + \frac{1}{R_{Nki}} \right) \end{cases} \quad (2)$$

ψ_{eqk} and R_{eqk} are the equivalent flux linkage and integrated reluctance of the k -th flux-barrier layer. The relationship between equivalent parameters and exported flux linkage ψ_{PMk} satisfies:

$$\Psi_{eqk} R_{eqk} = \Psi_{PMk} (R_{eqk} + R_{gk} + R_{\delta k}) \quad (3)$$

The total permanent magnet flux linkage is the superposition of output flux linkages from the three flux-barrier layers, which yields:

$$\Psi_{PM} = \sum_{k=1}^3 \Psi_{PMk} \quad (4)$$

From Eqs. (2) and (4), it is evident that the equivalent total MMF of the hybrid magnets is significantly higher than that of the single ferrite magnet. Under the condition of constant total flux-barrier volume, the series configuration directly enhances the air-gap main flux, which in turn increases the permanent magnet torque T_{PM} in Eq. (1), thereby achieving an effective improvement in the total electromagnetic torque.

2.3. Demagnetization Resistance Mechanism

Under heavy-load conditions, the negative d -axis armature reaction generates a demagnetizing field opposite to the magnetization direction of permanent magnets, which is the primary cause of irreversible demagnetization in ferrite magnets [5]. To mitigate this issue, this paper places high-coercivity NdFeB magnets on the air-gap side of each flux barrier and embeds ferrite magnets on the inner side, forming a series hybrid-magnet

configuration along the d -axis. A quantitative analysis of demagnetization resistance mechanisms is carried out as follows.

2.3.1. Outer Magnetic Shielding by High-Coercivity NdFeB

The reverse demagnetizing flux produced by armature reaction penetrates through the air gap into the rotor and first interacts with the outer NdFeB layers. By optimizing the dimensional ratio of the two magnet types, the operating point of NdFeB can be stably maintained within the linear region of its demagnetization curve [5]. As demonstrated in [27], for hybrid magnet motors, the key to enhancing overall demagnetization robustness is to make full use of the demagnetization resistance of high-coercivity materials, allowing them to bear more demagnetizing flux. Based on this mechanism, the outer NdFeB magnets in this paper share most reverse flux, effectively attenuating the demagnetizing field intensity that reaches the inner ferrite segments.

2.3.2. Flux Shunting via Rotor Iron Bridges

In the proposed equivalent magnetic circuit, each layer exhibits a common structure of four parallel branches that converge and then split. Taking the leftmost channel as an example: within each layer, the Y30 and N35 MMF sources form four parallel branches, corresponding to the inner/outer d -axis segments and left/right end segments. After convergence, the flux divides into two paths: one returns through the air-gap reluctance and iron-bridge reluctance of that layer; the other cascades to the next layer. The three layers are cascaded in series through the iron-bridge reluctances; the third layer closes to form a complete loop. Thus, the MMF sources are in parallel within each layer, while the layers are cascaded in series.

As demonstrated in [28], iron bridges provide low-reluctance bypass paths for the demagnetizing flux, allowing a large portion of the reverse flux to be shunted through the adjacent rotor iron bridges rather than penetrating the PM region. This effectively reduces the magnetic load on the PMs and mitigates the risk of irreversible demagnetization under heavy-load conditions. The flux-shunting mechanism has been demonstrated effective in similar bridge-type rotor structures [28], and its validity in the proposed topology is further confirmed by finite-element results in Section 4.4.

2.3.3. Flux Density Homogenization Effect

In conventional hybrid-magnet rotors, the two magnet types are often arranged side by side at the same radial position. The corners of the magnets near the air gap are prone to flux concentration, giving rise to localized high-intensity demagnetization hot spots. In this paper, a radial inner-outer series configuration is adopted, with NdFeB placed on the air-gap side and ferrite embedded inside. This structured arrangement effectively homogenizes the radial and tangential flux density distributions within the ferrite, eliminates local magnetic saturation at corners of the flux barriers, and avoids concentrated reverse magnetic fields. As verified by the finite-element results in the following section, the proposed topology exhibits no local irreversible de-

magnetization regions within the entire PM domain even under the extreme condition of six times the rated d -axis demagnetizing current.

In summary, the proposed radial inner-outer series hybrid-magnet topology integrates three synergistic magnetic circuit mechanisms: spatial shielding by the outer rare-earth magnets, flux shunting through the rotor iron bridges, and homogenization of flux density distribution. These three mechanisms work in coordination to attenuate the reverse magnetizing field imposed on the ferrite under heavy-load conditions. Compared with conventional parallel hybrid-magnet and pure ferrite rotor schemes, the motor's ultimate overload demagnetization resistance is significantly enhanced.

3. OPTIMIZATION DESIGN

3.1. Formulation of Optimization Problem

The design optimization of the proposed series hybrid-magnet rotor aims to reconcile three conflicting performance criteria, namely, average torque (T_{avg}), torque ripple (T_{rip}), and efficiency (η). These three objectives are selected because they collectively determine the motor's overall operational quality under rated conditions. The optimization problem is mathematically formulated as:

$$\min \left(\frac{1}{T_{avg}}, T_{rip}, \frac{1}{\eta} \right) \quad (5)$$

subject to the following performance constraints derived from benchmark requirements for motors of comparable power rating:

$$\begin{cases} T_{avg} > 21 \text{ N} \cdot \text{m} \\ T_{rip} < 10\% \\ \eta > 88\% \end{cases} \quad (6)$$

The efficiency is evaluated by accounting for all major loss components, including copper loss P_{cu} , iron loss P_{Fe} , and stray loss P_w , following the loss separation method detailed in [29]:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\% \quad (7)$$

$$P_{loss} = P_{Cu} + P_{Fe} + P_w \quad (8)$$

A total of 15 geometric parameters are initially considered as design variables, encompassing widths, thicknesses, and angular spans of both air flux barriers and embedded permanent magnets, as illustrated in Fig. 3. This high-dimensional parameterization, while necessary to capture the full design freedom of the complex rotor geometry, poses significant challenges to surrogate-based optimization, as elaborated in the following subsection. To tackle severe inter-layer magnetomotive force coupling and the high-dimensional design difficulty of the three-layer series hybrid-magnet rotor with NdFeB placed at the air-gap side and ferrite arranged on the inner side, three targeted optimizations are developed based on the standard sensitivity screening, surrogate modeling, and multi-objective optimization workflow to trade off optimization efficiency and

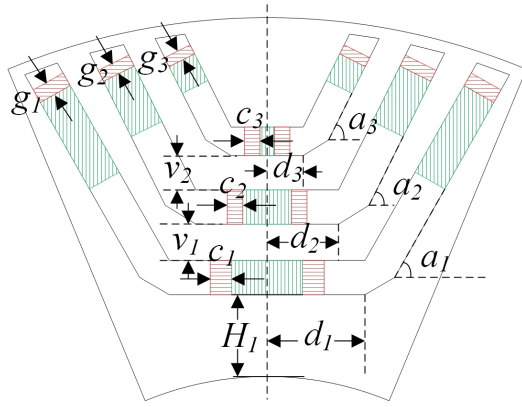


FIGURE 3. Design parameters of the motor geometry.

calculation precision. Firstly, a weighted comprehensive sensitivity index oriented toward low-vibration operating scenarios is proposed. Torque ripple is assigned the highest weight to filter dominant design variables, matching the low-noise demand of fan and pump driving loads. Secondly, a dedicated dimension-reduction strategy suitable for three-layer series-parallel magnetic circuits is established. It shrinks the original high-dimensional design space while completely preserving cross-layer flux-coupling features, preventing the topology's inherent anti-demagnetization capacity from being weakened after dimensionality reduction. Thirdly, a Kriging surrogate model adopting an automatic relevance determination Gaussian kernel is constructed. Layer-wise independent scale parameters are introduced to precisely characterize the magnetomotive force superposition behavior of series-connected magnets, elevating prediction accuracy under strongly coupled magnetic field conditions. The following subsections elaborate the optimization mathematical formulation, sensitivity-driven dimension reduction, surrogate model establishment, and NSGA-III optimization process in sequence.

3.2. Sensitivity-Driven Dimension Reduction

The direct construction of a surrogate model in the original 15-dimensional parameter space is impractical for two reasons. First, the required number of training samples for achieving acceptable prediction accuracy grows prohibitively with the input dimension, leading to an excessive finite-element computational burden. Second, the ill-conditioning of the correlation matrix in high-dimensional spaces degrades the numerical stability of the Kriging predictor. To circumvent these difficulties, a sensitivity-driven dimension-reduction procedure is performed as a prerequisite to surrogate modeling.

An initial sampling plan of 150 design configurations is generated using the Latin Hypercube Sampling (LHS) technique [30], which ensures uniform coverage of the entire 15-dimensional design space with a relatively small sample size. For each sampled configuration, the corresponding objective responses are evaluated via transient finite-element simulations under identical rated operating conditions.

The Pearson correlation coefficient is employed to quantify the linear dependence between each design variable and each

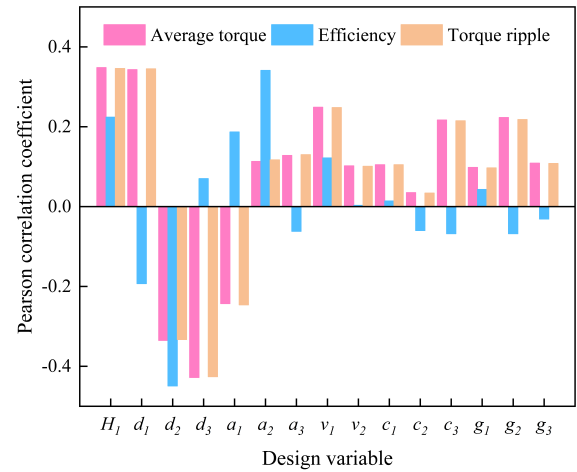


FIGURE 4. Sensitivity of design variables to optimization objectives.

objective:

$$\rho_{X_i, Y_i} = \frac{N \sum X_i Y_i - \sum X_i \sum Y_i}{\sqrt{N \sum X_i^2 - (\sum X_i)^2} \sqrt{N \sum Y_i^2 - (\sum Y_i)^2}} \quad (9)$$

where X_i represents the i -th design variable; Y_i represents the i -th optimization objective; and N is the number of samples.

Figure 4 presents the correlation matrix, in which the absolute value of each coefficient indicates the strength of influence.

To prioritize torque ripple suppression — which is widely recognized as the most critical indicator for PMaSynRMs due to its direct impact on vibration and acoustic noise — a weighted comprehensive sensitivity index is defined:

$$\begin{cases} S_{PMaSynRM}(x_i) = w_{Tavg} \cdot |S_{Tavg}(x_i)| + w_\eta \cdot |S_\eta(x_i)| \\ \quad + w_{Trip} \cdot |S_{Trip}(x_i)| \\ w_{Tavg} + w_\eta + w_{Trip} = 1 \end{cases} \quad (10)$$

where x_i is the design variable; $S_{Tavg}(x_i)$, $S_\eta(x_i)$, and $S_{Trip}(x_i)$ are Pearson correlation coefficients for average torque, efficiency, and torque ripple, respectively; and w_{Tavg} , w_η , and w_{Trip} are weight coefficients for average torque, efficiency, and torque ripple, respectively. Since torque ripple is the most critical indicator for this type of motor, w_{Trip} is set to 0.5, while w_{Tavg} and w_η are both set to 0.25.

Design variables are ranked in descending order of comprehensive sensitivity. A threshold of 0.2 is set as the criterion for classification: variables with a comprehensive sensitivity index greater than 0.2 are classified as the high-sensitivity layer, while those below 0.2 are classified as the low-sensitivity layer. According to the comprehensive sensitivity indices in Fig. 5, d_2 , H_1 , d_1 , d_3 , a_2 , and a_1 are finally selected as strongly correlated variables for further analysis, while the remaining parameters are fixed at their baseline values determined via preliminary finite-element parametric sweeps.

3.3. Surrogate Modeling in the Reduced Subspace

With the design space compressed to six dimensions, a Kriging surrogate model is constructed to approximate underlying functional relationships between retained geometric parameters and

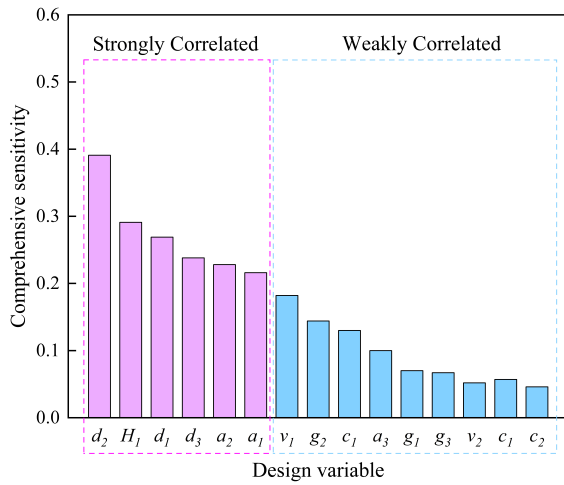


FIGURE 5. Comprehensive sensitivity of design variables to optimization objectives.

three performance objectives. The Kriging method is particularly advantageous for this application because it provides not only the predicted response values but also the associated prediction uncertainty, enabling efficient exploration of the design space with a limited number of training samples [28].

For any two sample points x_i and x_j in the reduced d -dimensional space (where $d = 6$), the spatial correlation is described by the Gaussian kernel function with Automatic Relevance Determination:

$$R(\mathbf{x}_i, \mathbf{x}_j) = \exp \left[- \sum_{k=1}^d \theta_k (x_{i,k} - x_{j,k})^2 \right] \quad (11)$$

where θ_k is the scale parameter for the k -th input dimension, controlling the correlation's sensitivity to variations in that dimension.

A refined LHS scheme generates 500 sample points exclusively within the reduced 6-dimensional subspace, and their objective responses are evaluated via finite-element simulations. The entire dataset is randomly partitioned into a training set (70%) and a testing set (30%). The coefficient of determination (R^2) for each of the three objectives consistently exceeds 0.95, confirming that the Kriging model established in this reduced subspace achieves sufficient predictive fidelity for reliable engineering optimization.

3.4. NSGA-III-Based Multi-Objective Optimization

The trained Kriging model is subsequently integrated into the NSGA-III algorithm as the fitness evaluator. NSGA-III is selected over its predecessor NSGA-II because the latter relies on a crowding-distance mechanism that tends to yield clustered solutions when handling three or more conflicting objectives. By contrast, NSGA-III employs a reference-point-based selection strategy that ensures both convergence toward the Pareto front and uniform distribution of obtained solutions [18].

It is worth emphasizing that, owing to the prior dimensionality reduction, the NSGA-III optimizer operates within a well-conditioned 6-dimensional latent subspace rather than the original 15-dimensional space. This subspace-constrained search

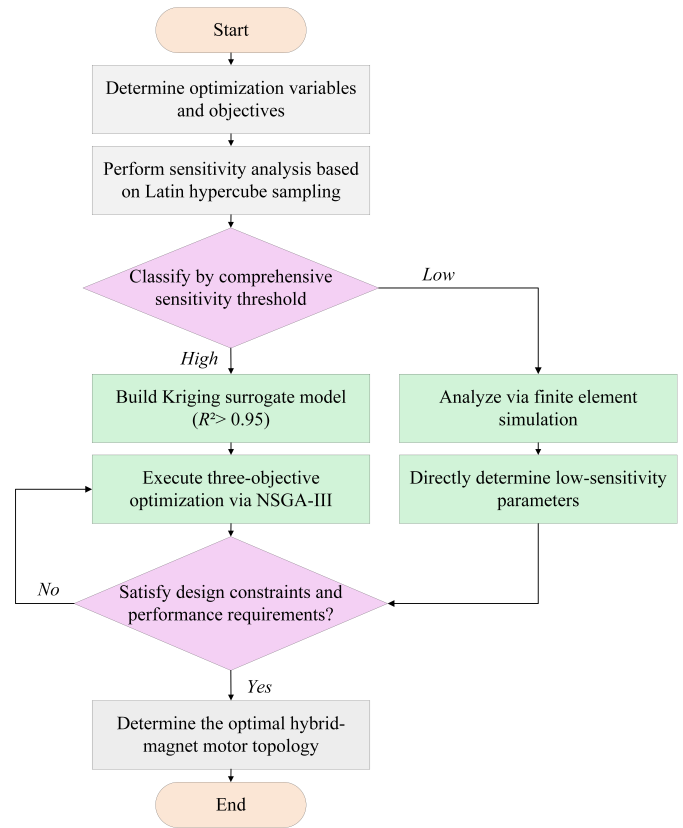


FIGURE 6. Flowchart of the optimization algorithm.

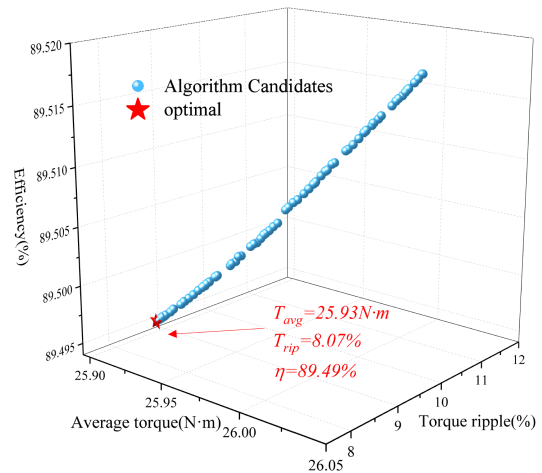


FIGURE 7. Pareto front (3D scatter plot of T_{avg} , T_{rip} , and η) obtained by NSGA-III.

not only accelerates algorithmic convergence but also mitigates the risk of overfitting the surrogate model, a common pitfall in high-dimensional surrogate-assisted optimization.

Algorithmic parameters are configured as follows: population size of 50, simulated binary crossover probability of 0.8, polynomial mutation rate of 50%, and maximal evolutionary generations of 100. The complete optimization workflow is illustrated in Fig. 6. The algorithm converges steadily to a uniformly distributed Pareto front, as shown in Fig. 7, without premature stagnation or excessive diversity loss. The final compromise solution is extracted from the Pareto set using the

TABLE 2. Key parameters and performance before and after optimization.

Item (unit)	Initial values	Optimal values
H_1 (mm)	8.5	7.18
d_1 (mm)	7	7.59
d_2 (mm)	4	5.26
d_3 (mm)	2	2.16
α_1 (°)	58	60.64
α_2 (°)	60	63.57
α_3 (°)	61	61.25
v_1 (mm)	3	3.09
v_2 (mm)	3	3.02
c_1 (mm)	-	1.89
c_2 (mm)	-	1.36
c_3 (mm)	-	1.36
g_1 (mm)	-	1.26
g_2 (mm)	-	1.05
g_3 (mm)	-	0.87
T_{avg} (N·m)	21.47	25.93
T_{rip} (%)	18.80	8.07
η (%)	85.56	89.49

fuzzy membership decision method, which identifies the solution with the highest overall satisfaction across all three objectives. The corresponding optimized geometric parameters and performance metrics are summarized in Table 2.

4. PERFORMANCE VERIFICATION AND ANALYSIS

Electromagnetic performances of the initial and optimized motors are compared using the finite element method under identical operating conditions (rated phase current of 5 A, rated speed of 1000 r/min) with consistent mesh density, time step size, and simulation duration for both models.

4.1. Magnetic Field Distribution

The magnetic field distribution under no-load conditions is analyzed to evaluate the magnetic circuit design. Fig. 8(a) shows the no-load flux-line distribution: flux lines are dense at rotor magnetic bridges and sparse inside flux barriers, indicating that flux barriers effectively guide flux paths and reduce leakage flux. Benefiting from NdFeB magnets arranged in the air-gap side of each flux barrier, divergent fringing flux at barrier openings is constrained, and the scattered magnetic lines near magnet ends are well homogenized, which fundamentally reduces concentrated leakage flux that triggers local demagnetization under overload. Fig. 8(b) shows the flux density contour: flux density at flux barrier ribs is uniformly distributed at 1.5 T without local oversaturation, and the overall flux distribution is reasonable.

4.2. Back-EMF and Air-Gap Flux Density

Air-gap flux density and no-load back-EMF are compared under no-load conditions at rated speed 1000 r/min.

Figures 8(c) and (d) show air-gap flux density waveforms and harmonic analysis. The optimized motor has higher amplitude and smoother waveform: fundamental flux density rises from 0.194 T to 0.351 T (80.93% increase), and the 15th harmonic amplitude decreases obviously, indicating improved sinusoidal property which helps reduce torque ripple and iron loss.

Figures 8(e) and (f) show no-load back-EMF waveforms and harmonic analysis. The optimized waveform is more sinusoidal, with fundamental amplitude increasing from 83.49 V to 151.54 V (81.53% increase). The 7th, 15th, and 21st harmonics are all reduced, and total harmonic distortion (THD) drops from 13.12% to 11.43% (1.69 percentage point reduction), verifying improved waveform quality.

4.3. Torque Characteristics

Electromagnetic torque waveforms under rated conditions are shown in Fig. 8(g). The initial motor has 21.47 N·m average torque and 18.80% torque ripple; after optimization, average torque reaches 25.93 N·m and torque ripple drops to 8.07%, with 20.78% torque increase and 57.07% ripple reduction.

Electromagnetic torque consists of reluctance torque and permanent magnet torque. The frozen permeability method is used for torque separation, with results shown in Figs. 8(h) and (i). The torque separation is performed at the Maximum Torque Per Ampere (MTPA) operating point, where the current angle is optimized to maximize the total torque for a given stator current. Under MTPA control, permanent magnet torque increases from 9.49 N·m to 13.24 N·m (39.52% increase), and reluctance torque rises from 11.97 N·m to 12.69 N·m (6.02% increase).

The results indicate that rotor flux barrier and hybrid magnet optimization significantly improve permanent-magnet torque and slightly raise reluctance torque, jointly contributing to the total torque increase.

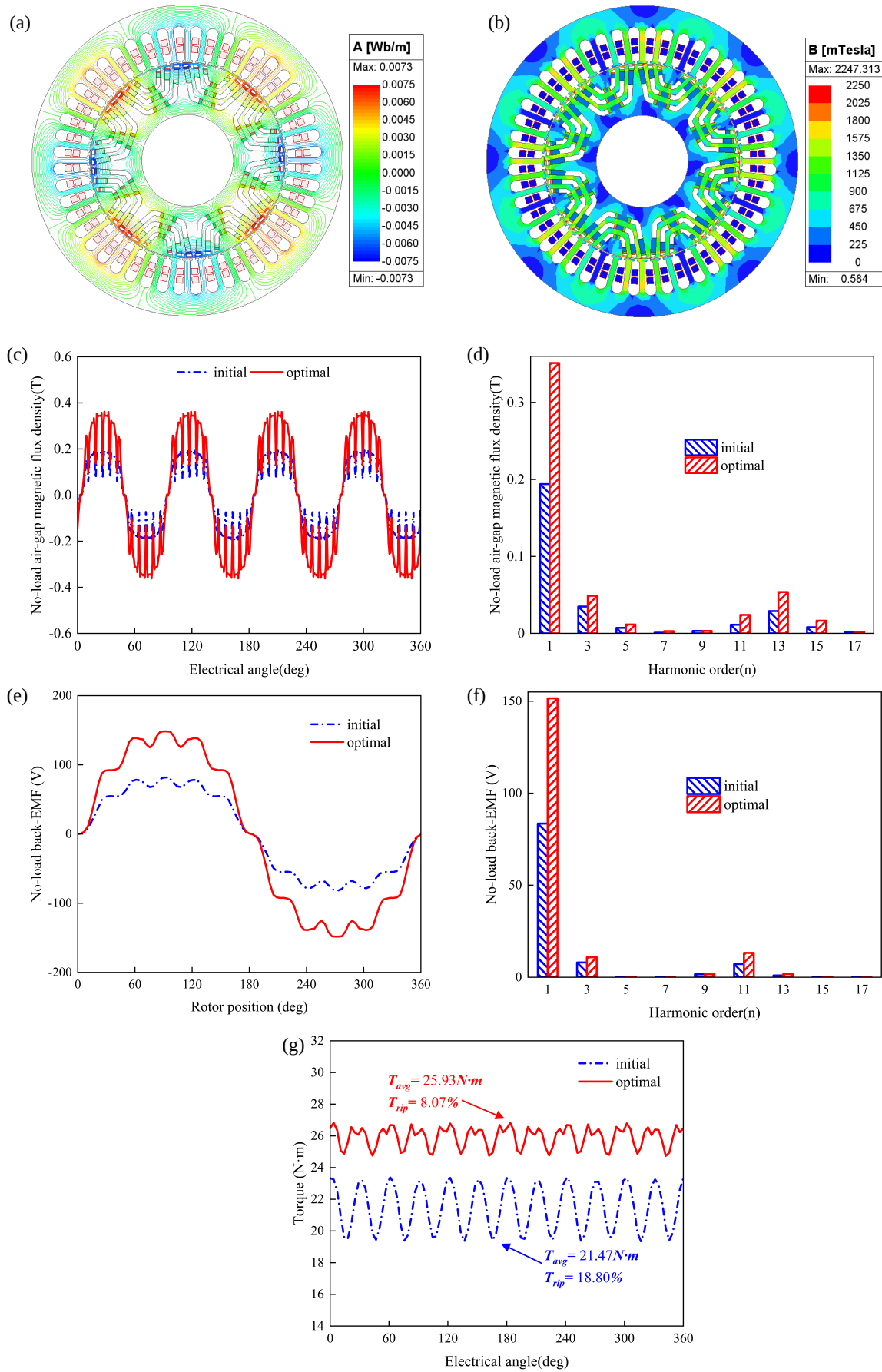
4.4. Overload Demagnetization Resistance Analysis

Ferrite permanent magnets feature low intrinsic coercivity, making them prone to irreversible magnetic attenuation when being subjected to reverse d -axis armature reaction under heavy overload. Unlike the pure ferrite asymmetric rotor discussed in our prior work [25], the proposed series ferrite-NdFeB hybrid rotor relies on a dual synergistic magnetic suppression mechanism to restrain demagnetization flux, which cannot be realized by single-component ferrite structures.

To quantitatively characterize the residual magnetic performance of PM units under extreme demagnetizing fields, the node-level demagnetization coefficient DemagCoef is defined as the ratio of residual remanence after overload excitation to the original virgin remanence of the same finite element, as expressed in Eq. (12):

$$D_{mag-coef} = \frac{B_{r,rec}}{B_{r0}} \quad (12)$$

A coefficient close to 1.0 means that no magnetic attenuation occurs. Consistent with widely adopted industrial evalua-



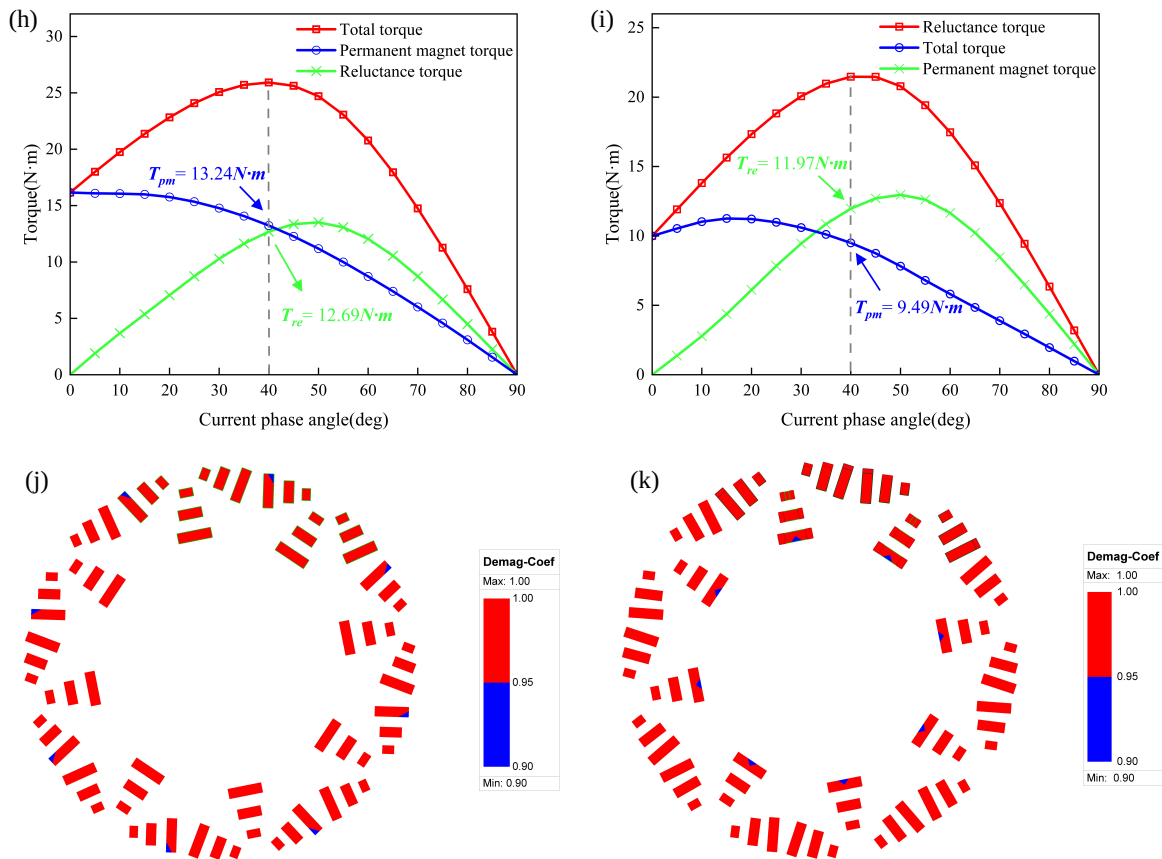


FIGURE 8. Comprehensive performance comparison. (a) Flux line distribution, (b) flux density contour, (c) air-gap flux density waveform, (d) air-gap flux density harmonics, (e) back-EMF waveform, (f) back-EMF harmonics, (g) torque comparison, (h) torque decomposition before optimization, (i) torque decomposition after optimization, (j) demagnetization coefficient distribution before optimization, and (k) demagnetization coefficient distribution after optimization.

tion criteria for ferrite machines [31–33], $\text{DemagCoef} = 0.95$ is set as the critical safety boundary; areas with values below this threshold are marked as irreversible demagnetization zones.

Two extreme demagnetization operating conditions are set for horizontal comparison: a pure d -axis demagnetizing current of 3 times the rated value ($i_d = 3I_{\text{rated}}$, $i_q = 0$) for the benchmark full-ferrite rotor and a more severe condition of 6 times the rated value ($i_d = 6I_{\text{rated}}$, $i_q = 0$) for the optimized hybrid-magnet rotor.

As illustrated in Fig. 8(j), the single ferrite benchmark rotor has large blue low-coefficient zones concentrated at the shaft-side magnet ends at all magnet corners under only three times rated current, where DemagCoef drops to 0.90–0.95, which verifies severe localized irreversible demagnetization defects of pure ferrite topologies.

In sharp contrast, the optimized series hybrid rotor (Fig. 8(k)) maintains nearly all magnet domains above the 0.95 safety limit even under double the overload intensity (six times rated demagnetizing current), with only tiny, negligible weak demagnetization spots visible. The concentrated end demagnetization phenomenon is completely eliminated, which fully demonstrates that air-gap-side NdFeB can converge magnetic flux and buffer reverse demagnetizing fields effectively.

The outstanding anti-demagnetization capacity originates from two exclusive magnetic circuit synergies unique to this series hybrid layout, which are absent in the all-ferrite structure of [25]:

Outer high-coercivity NdFeB shielding barrier: Combined with the no-load flux distribution in Fig. 8(a), NdFeB restrains divergent fringing flux at barrier openings and homogenizes the internal magnetic field of permanent magnets. NdFeB magnets are placed on the air-gap side of each flux barrier. The high-coercivity rare-earth layer bears most of the reverse demagnetization flux penetrating from the air gap, directly attenuating the demagnetization field intensity that reaches inner ferrite segments.

Parallel magnetic bridge flux shunting path: Ferrite and NdFeB are connected in series inside each magnetic barrier, while multiple barrier branches form parallel magnetic loops with rotor iron bridges. A large proportion of reverse demagnetizing flux bypasses the permanent magnet array and circulates through low-reluctance rotor bridges, greatly reducing the magnetic load borne by ferrite magnets.

The combination of rare-earth shielding and magnetic flux shunting forms a two-layer suppression loop for demagnetization fields, fundamentally improving the overload reliability of

the hybrid PM rotor compared with conventional single-ferrite PMSynRM schemes.

4.5. Efficiency Performance

The optimization objectives of this paper include average torque, torque ripple, and rated efficiency, and all finite element efficiency calculations are carried out under rated operating conditions (5 A phase current, 1000 r/min). The efficiency calculation model comprehensively accounts for stator copper loss, stator and rotor iron loss, and stray loss, as described in Eq. (7) and Eq. (8).

As shown in Table 2, the efficiency of the initial all-ferrite benchmark motor reaches 85.56% under rated steady-state operation, and the optimized hybrid-magnet motor achieves a rated efficiency of 89.49%, representing a 3.93 percentage point efficiency improvement. The efficiency gain mainly stems from two aspects: first, the enhanced fundamental air-gap flux density raises permanent magnet torque output, which reduces the required stator current to deliver the same target torque and significantly cuts winding copper loss; second, the optimized rotor flux barrier structure homogenizes the internal magnetic field, weakens local magnetic saturation, and suppresses high-order air-gap flux harmonics, thereby lowering iron loss.

In practical industrial driving scenarios, such as fans, pumps, and compressors, the motor runs around rated load for most of its service cycle, making rated efficiency the key energy-efficiency evaluation index. Under light loads, the proportion of no-load iron loss increases, resulting in a slight efficiency drop relative to rated operation. The 3 times and 6 times rated demagnetizing current conditions in Section 4.4 are merely transient extreme states for demagnetization verification rather than continuous operating points. Severe overload brings drastically increased copper loss and notable efficiency deterioration, so a full-range efficiency map is not supplemented in this work.

4.6. Manufacturing Assembly Process and Engineering Applicability of the Rotor

In view of requirements of industrial mass production, supplementary analysis on manufacturing and assembly characteristics of the proposed radial layered series hybrid-magnet rotor with U-shaped flux barriers is carried out. The rotor adopts integrally stamped enclosed U-shaped flux barrier cavities with built-in limiting slots, which restrict the air-gap-side NdFeB magnets and inner ferrite magnets radially and circumferentially. Axial compression by insulating end plates at two ends can resist centrifugal force at high speed without metal retaining sleeves. The separated arrangement of two magnet materials alleviates stress cracking induced by inconsistent thermal expansion coefficients.

Flux barrier cavities are manufactured by high-precision progressive stamping, and the dimensional repeatability of stamped cavities is controlled within ± 0.015 mm. A tiny assembly clearance of 0.02–0.04 mm is reserved between the magnet and lamination cavity to compensate for sintering di-

mensional deviation of permanent magnets and stamping errors of silicon steel sheets. This sequential embedding structure of two radial magnet layers avoids complex interleaved stacking processes, leading to far less accumulated assembly tolerance than traditional interleaved multi-layer hybrid rotor schemes.

The whole mass production is realized through automated pipelines including standardized magnet sorting and cutting, automatic lamination stacking and riveting, as well as robotic unified end plate pressing. Magnets are pre-sorted by thickness to screen out unqualified workpieces; integral rotor stacking guarantees the coaxiality and circumferential uniformity of all flux barriers, and fixed compression parameters of automatic equipment eliminate uneven clamping force brought by manual operation. Besides, all unit flux barriers around the rotor share identical geometric dimensions, which effectively avoids air-gap magnetic field unbalance caused by inconsistent manual assembly. The proposed rotor balances superior electromagnetic performance and manufacturability, possessing promising prospects for practical industrial application.

5. CONCLUSION

This paper proposes a hybrid-magnet PMSynRM with ferrite and NdFeB arranged in series within each flux barrier and establishes a Kriging-NSGA-III multi-objective optimization framework. The main conclusions are as follows:

- (1) The sensitivity analysis reduces 15 geometric variables to 6 dominant parameters. The Kriging surrogate model achieves ($R^2 > 0.96$) for all three objectives, accurately replacing finite element simulations. The NSGA-III optimizer successfully yields a well-distributed Pareto front, demonstrating the efficiency and reliability of the proposed optimization framework for hybrid-magnet motor design.
- (2) Compared with the initial all-ferrite benchmark motor, the optimized hybrid-magnet motor achieves a 20.78% increase in average torque (from 21.47 N·m to 25.93 N·m), a 57.07% reduction in torque ripple (from 18.80% to 8.07%), and maintains a high efficiency of 89.49%. The fundamental air-gap flux density and back-EMF are enhanced by 80.93% and 81.53%, respectively, while the total harmonic distortion (THD) decreases from 13.12% to 11.43%, indicating significantly improved sinusoidal waveform quality.
- (3) More importantly, the series-connected magnetic circuit provides a dual anti-demagnetization mechanism absent in conventional all-ferrite designs: the outer-layer NdFeB shields the demagnetizing field, while parallel rotor bridges shunt the reverse flux away from the ferrite magnets. As a result, the proposed motor exhibits no visible irreversible demagnetization even under six times the rated d -axis demagnetizing current, whereas the all-ferrite benchmark already shows large-area demagnetization zones under only three times the rated current. This confirms a substantial overload safety margin for the hybrid topology.

To further verify theoretical and finite-element results obtained in this paper, future work will focus on prototype manufacturing and experimental validation under real inverter-fed conditions. A 2.2 kW prototype will be fabricated based on the optimized parameters, and its steady-state and transient performances will be tested under both rated and overload conditions. Additionally, temperature-dependent demagnetization tests will be conducted over a range of operating temperatures to evaluate thermal stability, and the proposed hybrid-magnet concept will be extended to higher power ratings and alternative pole-slot combinations.

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